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1 Low carbon oil production: Enhanced Oil Recovery with CO₂ from North Sea Residual Oil 2 Zones

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10 Abstract

11 Residual Oil Zones (ROZ) form when oil has leaked or migrated from a reservoir trap
12 through geological time, leaving a zone of immobile oil. Here we assess the feasibility of
13 ROZ production with CO₂ flooding, in a North Sea oil field for the first time. We identify a
14 hydrodynamically produced ROZ, with an oil saturation of 26%, in the Pierce Oil Field of the
15 Central North Sea and adapt established recovery factors for Carbon Dioxide Enhanced Oil
16 Recovery (CO₂ EOR) from onshore fields, to estimate oil resource and CO₂ storage potential.
17 Our mid case results show that CO₂ utilisation increases commercial reserves by 5-20%
18 while storing 15Mt CO₂. Based on our calculations CO₂ EOR can produce low carbon
19 intensity crude oil from a mature basin and could store more CO₂ than is released from the
20 production, transport, refining and final combustion of oil.

21 Introduction

22 Since the discovery of oil by Edwin Drake in 1859¹ the conventional oil industry has
23 developed great expertise in locating positions in the subsurface, into which oil has
24 accumulated by buoyancy, after migration away from its source rock. Within an oilfield, the
25 vertically layered fluid transition is seldom a simple Oil Water Contact (OWC), but is
26 gradational vertically downwards from a zone of mobile oil, the main pay zone (MPZ), into
27 water containing pores. This is defined as a transition zone, the thickness of which depends
28 on capillary forces, below which is the free water level (FWL) (Figure 1A).

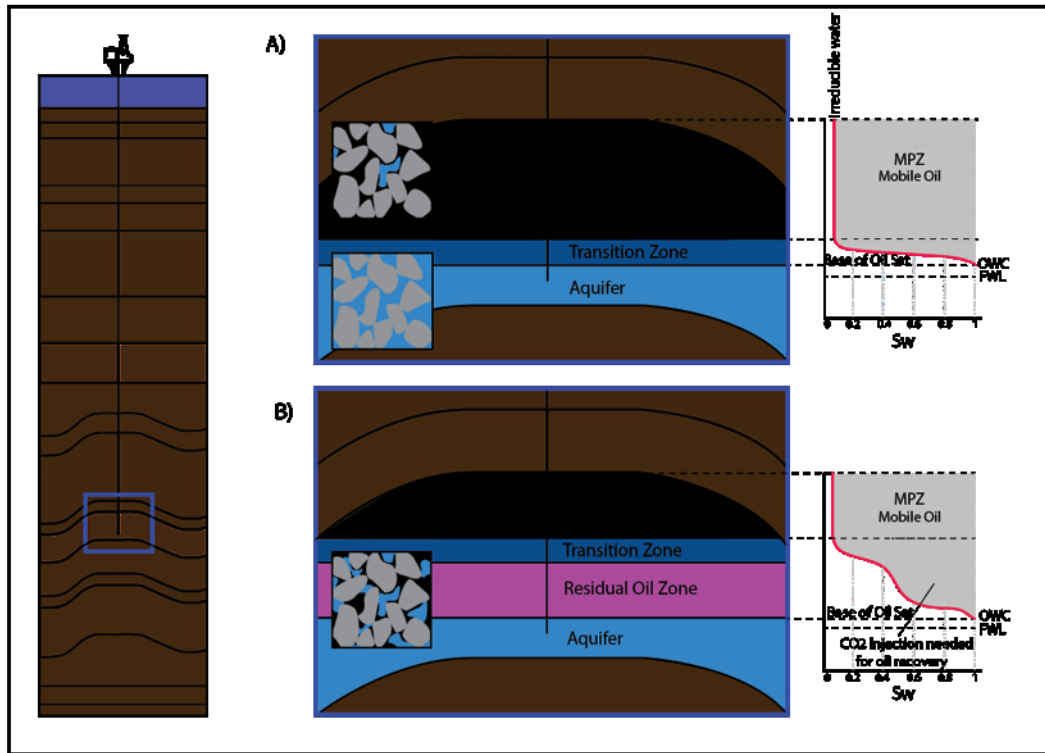
29 What has not been fully understood in the North Sea and most other oil basins globally, is
30 that Residual Oil Zones (ROZ) exist where a number of natural geological conditions have
31 caused the remobilisation of oil out of a reservoir. This natural remobilisation causes the
32 OWC to rise within the oil reservoir leaving behind residually trapped oil (Figure 1B).
33 Although the remaining oil saturation may be similar to an oil field that has undergone
34 primary production and water-flooding, the formation of a ROZ results from natural
35 processes, not from engineered oil production. ROZ oil has not been commercially declared
36 as a reserve, because it historically has not considered recoverable. With many large oil
37 fields in established basins reaching near depletion, and a move to reduce the CO₂

38 emissions of producing oil, the oil reserves and CO₂ storage potential in ROZ is of economic
39 and strategic interest.

40 The concept of these zones holding recoverable reserves has to date only been applied to
41 the United States with work primarily being focussed on the Permian Basin², with no
42 previous studies on North Sea oil fields. The origins and resource potential of ROZ below oil
43 fields in North America has been discussed in detail by Koperna et al. (2006)³, Advanced
44 Resources⁴ and Melzer et al. (2006).⁵ Melzer et al. (2006)⁵ identified three main processes
45 in which oil columns can be naturally drained causing the creation of ROZ: the onset of
46 hydrodynamic flow; breached and reformed reservoir seals; regional or local basin tilt.
47 Here, we investigate how hydrodynamic flow (discussed below) in the Central Graben of
48 the North Sea basin, may lead to the creation of ROZ that can be developed with CO₂
49 injection for enhanced oil recovery (CO₂ EOR).

50 By reviewing literature and well logs, the Pierce Oil Field was identified to have a ROZ. By
51 further analysing well logs and building a 3D geological model of the Pierce Oil Field, we
52 show for the first time that ROZ do occur in North Sea oil fields, and have potential to
53 increase recoverable reserves by up to 20%. With evidence from North America, we
54 propose that ROZ oil can be produced by injection of CO₂ as a solvent. Further injection of
55 CO₂ into the oil field can more than offset the additional carbon created by producing oil
56 from the ROZ.

57



58

59 Figure 1 – A) Schematic representation (left) of a generalised oil field with (centre) an oil column and transition
 60 zone below. Inset graphs (right) show that oil saturation ($1-S_w$) varies from ~90% (10% irreducible water
 61 saturation) above the OWC to 0% at the bottom of the transition zone (100% free water level- FWL). B)
 62 Schematic representation of oilfield with ROZ, where the oil column has previously been thicker. Oil has been
 63 removed by natural geological process, such as hydrodynamic tilting, and has left a ROZ. Although ROZ will
 64 produce only water when developed under primary or secondary production, they produce oil when CO_2 is
 65 injected.

66 Carbon Dioxide Enhanced Oil Recovery and Residual Oil Zones in North America

67 In North America, CO_2 EOR is an established technology used to produce incremental oil
 68 from oil fields that have been depleted or water flooded. The injection of pure CO_2 reduces
 69 oil viscosity (increasing oil mobility) and increases reservoir pressure and oil volume⁷⁻¹⁰
 70 causing residually trapped oil to move towards production wells. Developed commercially
 71 in the 1970s, CO_2 EOR is currently utilised in over 130 oil fields in United States¹¹ where it is
 72 primarily deployed in oil fields that have been depleted through engineered production.

73 In the Permian basin of Texas, 8 fields are currently using CO_2 EOR to produce oil from the
 74 ROZ, with over 6500 barrels of oil being produced per day^{12,13}. The fields that are currently
 75 producing from the ROZ use CO_2 injection to produce from both the ROZ and the MPZ
 76 above. However CO_2 EOR from the ROZ are not only targeted at zones which have depleted
 77 MPZs, as one of the 6 currently planned CO_2 EOR ROZ developments are targeting a
 78 'greenfield ROZ' where no depleted field exists above the ROZ¹². These 'greenfield' zones,
 79 the formation and history of which is explained in detail in Trentham et al. (2012)¹², are
 80 thought to have been formed when a combination of water charge and tectonic uplift,
 81 which causes elevated piezometric pressure⁶, has caused large regional formations, such as

the San Andreas Formation, to be 'naturally water-flooded'. This water charge is believed to have swept the oil in paleo-traps, leaving regional scale zones of residual oil behind¹².

Although only a small number of fields are currently producing from the ROZ, the resource potential for the US is estimated to be large. As summarised by Godec et al. (2013)¹³ work by ARI and Melzer Consulting has identified up to 42 billion barrels of oil in place below existing fields in the Permian, Big Horn and Williston basins^{4,14,15}. Further work by Melzer Consulting has highlighted that up to 100 billion barrels of oil in place may exist in 'greenfield' ROZ fairways in the Permian basin alone ¹². Initial reservoir modelling work estimates that 13 billion barrels of oil is economically recoverable from ROZ below established oil fields in the Permian basin and 20 billion barrels may be economically recoverable from 'greenfield' ROZ in the Permian basin with CO₂ injection. Kuuskraa et al. (2013)¹⁶ estimate that the CO₂ demand from developing ROZ below US oil fields and 'greenfield' ROZ may be up to 13 billion metric tonnes over the life of the projects. Considering the US has annual CO₂ emissions of over 5 billion Mt the potential CO₂ demand from CO₂ EOR is not insignificant.

Characterising Residual Oil Zone potential at a field scale

Once a target ROZ has been identified a number of studies have proposed different methods to determine both the existence and potential recoverability of oil from the ROZ. Honarpour et al. (2010)¹⁷ completed a rock-fluid characterisation for miscible CO₂ injection in the ROZ at the Seminole field in the Permian basin. They present a method for firstly estimating the remaining oil saturation through a range of core and core scale water-flood tests before also characterising formation anisotropy and scale dependent permeability. Then residual oil saturation after miscible CO₂ flooding is predicted from core scale CO₂ flood tests at reservoir pressures and temperatures. The rock and fluid properties, when integrated into a geocellular model, can then be used to run a compositional CO₂ flood to assess field scale recoverability from the ROZ.

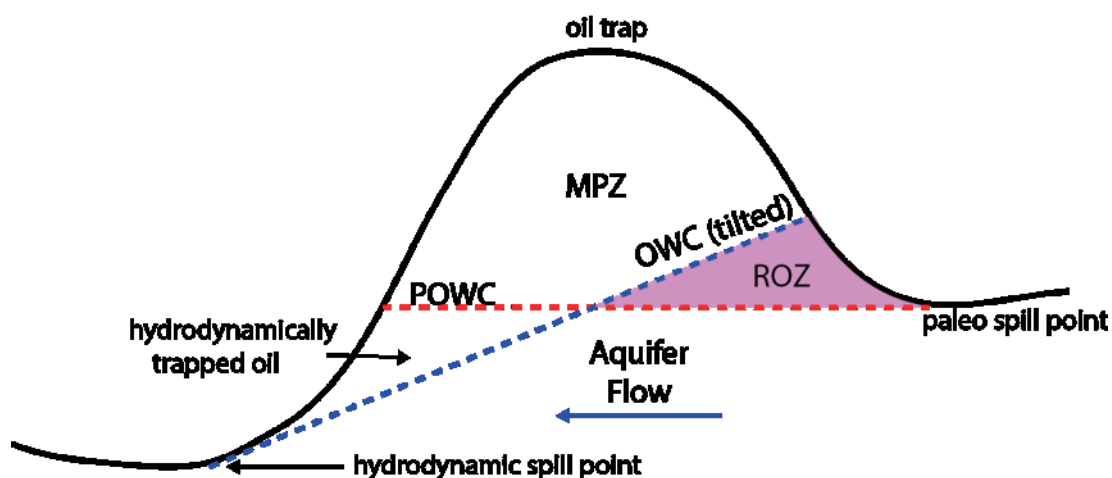
Pathak et al. (2012)¹⁸ also present a method for evaluating the ROZ potential at the Means field in the Permian basin. Focussing on reservoir uncertainty and methods to predict the remaining oil saturation in a field, Pathak et al. (2012)¹⁸ note that the major reservoir uncertainties derive from defining the remaining oil saturation, the recovery efficiency and timing of oil recovery of CO₂ EOR in the ROZ and the presence of leach zones or thief intervals. They also note that other reservoir uncertainties such as facies distribution, the presence of vertical flow barriers and baffles and well injectivity limitations, although relevant, are less significant uncertainties. Here a similar method to that described in Honarpour et al. (2010)¹⁷ is applied to the Pierce Oil Field to estimate the oil resource potential and CO₂ storage resource in the ROZ. To date, this resource estimation has not been completed on a North Sea oil field.

121 Hydrodynamic principles

122 Hydrodynamic flow of 'active' aquifer water upwards and outwards from deep basin
123 geopressed zones in the Central Graben of the North Sea causes OWCs to tilt, leaving
124 zones of residual oil. In North America, ROZ created through hydrodynamic processes
125 typically contain 10-40% immobile oil in the pore space.^{17,19} This is a similar oil saturation to
126 many of the fields in the North Sea basin which have undergone primary and secondary
127 production (water-flooding). If similar oil saturations are found in North Sea ROZ, then
128 these are targets for CO₂ EOR.

129 Under static aquifer conditions the hydrocarbons within an oil accumulation have a flat
130 contact with the saline aquifer brine below. If the structure has been filled to spill, the
131 structural spill point will control how much hydrocarbons the trap can hold. If the structure
132 continues to be charged with migrating oil, then hydrocarbons will leak from the structural
133 spill point. However in oil fields with an underlying active aquifer, hydrodynamic flow and
134 the resultant tilting of the OWC may cause the spill point to move to one that is
135 hydrodynamically controlled.²⁰⁻²⁴ When this occurs creating an asymmetric hydrocarbon
136 trap, the new spill point may be deeper than the structural spill point in the direction of
137 pressure decrease, trapping additional hydrocarbons beyond the known trap. Towards the
138 direction of aquifer inflow, the OWC will move above the structural spill point. Where this
139 OWC has retreated from the structural spill point to the new hydrodynamically controlled
140 OWC, a zone of residual oil is left (Figure 2).

141



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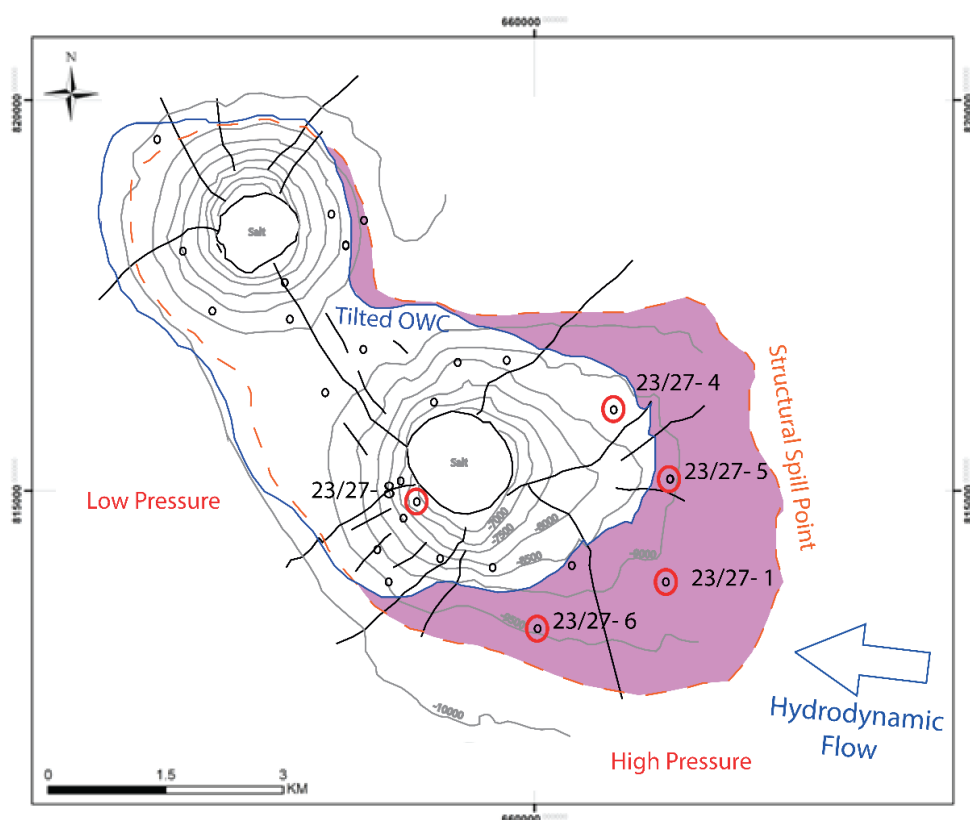
143 Figure 2- Schematic representation of hydrodynamic flow and the creation of ROZ. The paleo oil water contact
144 (POWC), before the onset of hydrodynamics, is highlighted in red. The pressure gradient across an oil field
145 causes the FWL (free water level, here noted as oil water contact) to tilt in the direction of lowest pressure,
146 leaving a wedge of residual oil (pink), with a new hydrodynamic spill point being created.

147

148

149 Residual Oil Zone potential at the Pierce Oil Field- a case study

150 The Pierce Oil Field is located in Blocks 23/22a and 23/27 of the UK Central North Sea,
 151 adjacent to the UK/Norway median line in 85m of water. The field is characterised by the
 152 accumulation of oil and free-gas caps within the Palaeocene Forties Sandstone Member, on
 153 the flanks of two Permian Zechstein salt diapirs that are separated by a 1.5km wide
 154 structural saddle.²⁵⁻²⁷ The field is characterised by large variations in the measured OWCs
 155 which were identified by both well log and pressure data in the appraisal wells that were
 156 drilled in the 1970s. Across the field a general deepening trend in the OWC towards the
 157 west is observed with over 300m of vertical relief between the shallowest and deepest
 158 OWCs observed in the field (Figure 3). This equates to a dip of 90m/km.²⁰ Although
 159 different theories exist to explain the variation in OWCs at the Pierce Field,^{26,28} a number of
 160 studies have proposed that it is hydrodynamically controlled.^{20,21,29} We propose that
 161 hydrodynamic tilting of the OWC has aided in the creation of a ROZ, in the definition of
 162 Melzer et al. (2006).⁵



163

164 Figure 3- Top reservoir structure map of the twin salt diapir Palaeocene Pierce Field, adapted from Porter
 165 (2011).²⁷ The present day oil water contact (blue) has a vertical relief of 300m and is below the structural spill
 166 point in the NW sector of the field but sits above the structural spill point in the SE sector of the field. The ROZ
 167 (pink) lies between the structural spill point and the current OWC in the SE sector of the field. Before the
 168 location of the OWC was known and the hydrodynamic theory proposed, 4 wells (23/27- 1,4,5,6) were drilled in
 169 the SE sector above the structural spill point. N.b well 23/27-4 has been interpreted by some to lie down dip of
 170 the OWC and so has been included in this study.²⁷

171 The identification of a producible ROZ at South Pierce has not been made previously,
172 although a number of studies have highlighted that wells that were drilled in the SE sector
173 of Pierce within the structural closure were 'dry holes' i.e. did not flow oil during drill stem
174 tests.^{20,21,29} These studies infer that wells in the SE sector of the South Pierce Field contain
175 residual oil due to a retreating hydrodynamically controlled OWC but do not identify it as a
176 producible zone.

177 **Methods**

178 **Constructing a static geological reservoir model of the ROZ at the South Pierce Field**

179 To estimate the volume of oil in place and potential CO₂ storage volume of the ROZ at the
180 Pierce Field a basic 3D geological model was constructed using MOVE™. A summary of the
181 model building method can be seen in Figure 4. The top Forties Horizon was constructed
182 using a structural contour map derived from 3D seismic.²⁷ Well deviation data and
183 composite logs were taken from the UK Oil and Gas Data- Common Data Access Database
184 (CDA) for 14 appraisal wells drilled through the North and South Pierce Field. Top Forties
185 Member sandstone well tops were taken from composite well logs and used to tie surfaces
186 to the correct depth (TVDSS). It is thought that the depth uncertainty in the seismic derived
187 surfaces is around 30-60m, due to the difficult seismic imaging at the salt- reservoir
188 boundary. Due to the lack of publicly available seismic data, or structural contour maps for
189 the Bottom Forties Member, the bottom Forties Member surface was projected from the
190 top reservoir surface using an orthogonal constant bed thickness of 122m. Although this
191 thickness was estimated from well data and from thickness data within Birch & Haynes
192 (2003)²⁵ it only represents an average for the formation. Well tops derived from composite
193 well logs were also used to tie the bottom surface to the correct true vertical depth
194 (TVDSS). A surface depicting the pre-production tilted OWC was constructed from contour
195 data presented in Porter (2011).²⁷

196 As the ROZ is depicted by the zone between a paleo oil water contact (POWC) and a pre
197 production OWC, the POWC also had to be defined for Pierce. Although there is debate
198 within the literature, it was assumed for this study that the POWC lies at the depth of the
199 structural spill point for the trap at -3008m TVDss.²⁵ To create a bottom surface for the
200 deepest extent of a ROZ, the horizontal surface representing the structural spill point was
201 merged with the bottom Forties surface, for when the bottom Forties is above -3008m
202 (above the structural spill point). The top surface for the ROZ was created by merging the
203 present day pre-production OWC (where it is split by the top and bottom forties surface)
204 with the Top Forties surface. Creating these two surfaces that represent the top and
205 bottom extents of the residual zone allowed a geocellular volume to be created that could
206 be populated with core and well log data to estimate the oil in place and CO₂ storage
207 capacity of the ROZ (Figure 4). As can be seen in Figure 5, in wells 23-27-1 and 23-27-5 the
208 ROZ extends from the top Forties Sandstone Member to bottom Forties Sandstone
209 Member. In well 23-27-4 only around 12m of ROZ is penetrated. The ROZ at South Pierce
210 was found to have a bulk rock volume of $982 \pm 184 \times 10^6 \text{ m}^3$. The uncertainty in the estimate
211 is derived predominantly from the seismic depth uncertainty of 30-60m in the 122m thick

Forties Sandstone Member which equates to an error of 38% (45m error in 122m thickness). However because surfaces are tied to well data this seismic error is not present throughout the surface. By combining the well error, taken as 0%, and the seismic error of 38% an error of 19% is used for the total volume.

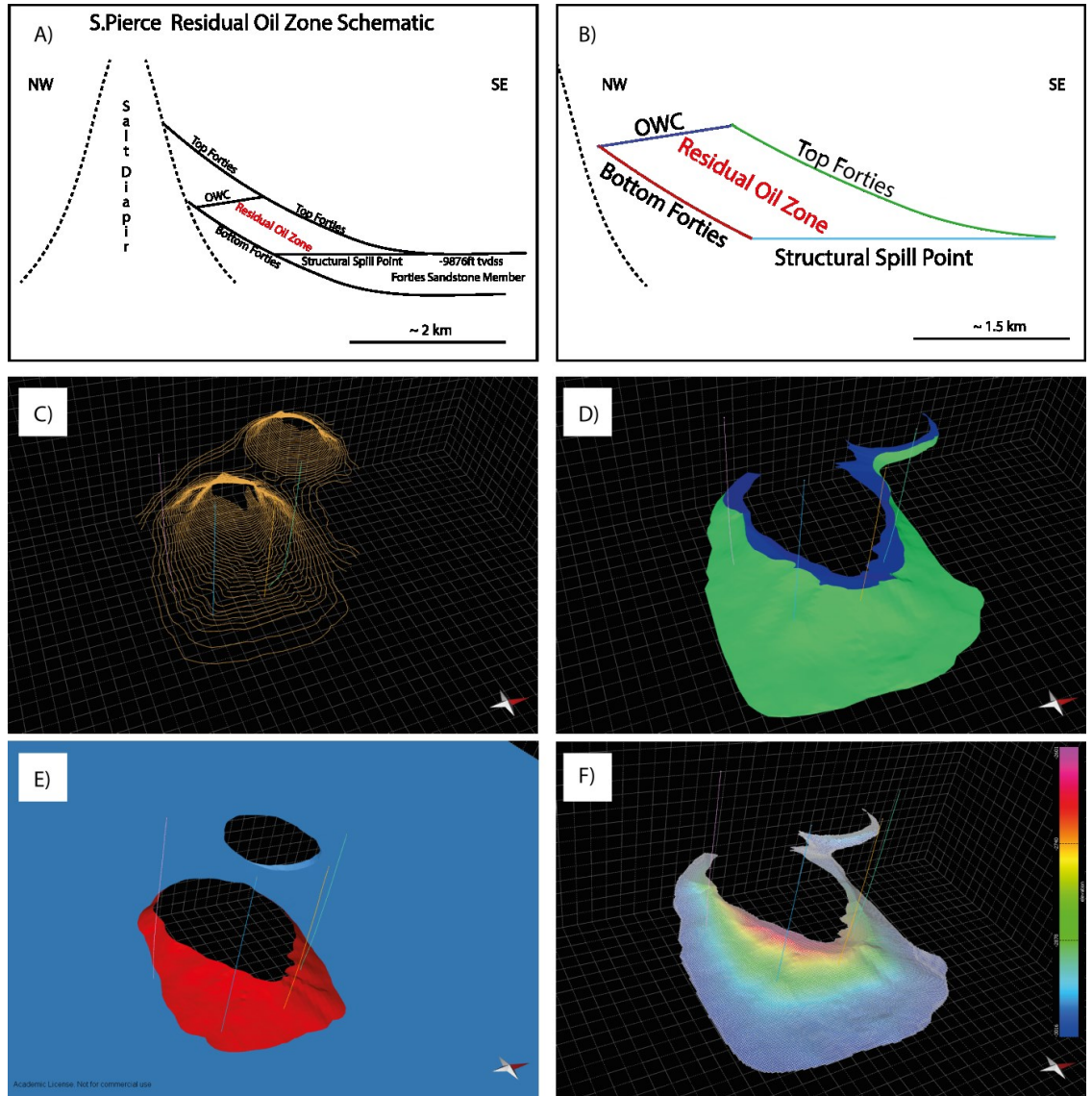


Figure 4 – A) South Pierce schematic summary B) 4 surfaces selected to build residual oil zone volume C) Top reservoir surface contours. Top surface was constructed from published top reservoir structure maps and corrected using well data D) Top Forties surface (green) was cut and merged with the current oil water contact surface (dark blue) E) The bottom Forties surface (red) was constructed by projecting the top reservoir surface with a constant bed thickness of 122m. Well data was also used to correct the surface depths. F) Geocellular model representing the bulk rock volume of the ROZ at South Pierce- colours represent depth with red shallow and blue deep.

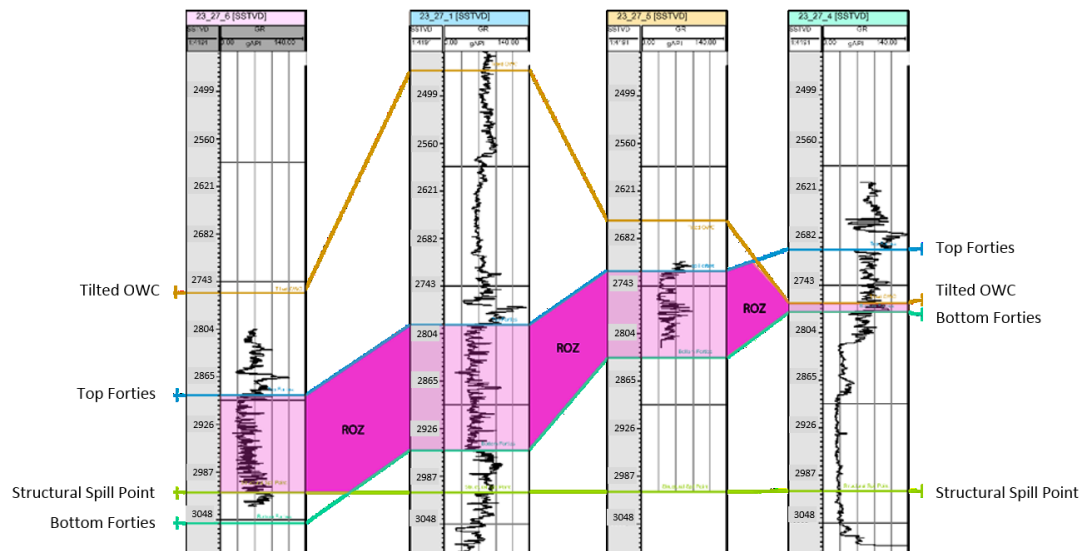


Figure 5 - Well log summary with gamma ray of the four wells thought to penetrate the ROZ at the South Pierce Field.

Log and core data from four wells (23/27- 1,4,5 & 6) (See Figure. 3 for location), which penetrate the ROZ at South Pierce were used to populate the bulk rock ROZ volume with porosities and NTG. Residual oil saturation values were available from core analysis. However it is thought that due to post core extraction leakage that these values would under estimate the in-situ remaining oil saturation.^{17,30} Techniques such as sponge coring, where the expelled oil is captured after core cutting, are not thought to have been carried out in the core analysis of the wells at South Pierce. As highlighted by Honarpour et al. (2010)¹⁷ pressure retained coring is the preferred technique for determining remaining oil saturations, but is not currently practised due to the costs and risks involved.

In situ oil saturation was therefore estimated using Archie's water saturation (S_w) equation³¹ (See Supplementary Information for more details). This well log method, alongside core analysis, log inject log (LIL) and chemical tracer tests, was also used by Pathak et al. (2012)¹⁸ to determine oil saturation for EOR projects. Chang et al. (1988)³⁰ who evaluated and compared different methods to determine residual oil saturation estimated that oil saturation predictions using resistivity logs may be slightly higher than in other methods. It also must be noted that the oil saturations in a ROZ will be locally variable and the estimation of oil saturation will never be without uncertainty.

Monte Carlo simulation of data at South Pierce

To estimate the total oil in place for the ROZ at South Pierce a Monte Carlo approach was used using R-Studio™. For bulk rock volume, NTG and porosity random sampling between the minimum and maximum range of values was used for the 20,000 iterations run. For porosities a random value was sampled between the range of mean porosity from each well. This was completed using a 'runif' statement to randomly sample a value between the input ranges. Water saturation values were sampled from a merged dataset of all

260 minimum, mid and maximum S_w from all four wells, which equated to 2244 S_w values. No
 261 well was given any sampling preference over another. Recovery factors were also estimated
 262 to calculate the recoverable reserves from the ROZ at South Pierce. Given the lack of
 263 experience of CO₂ injection into ROZ in the North Sea, analogue recovery factor values of 5-
 264 25% of oil in place, were taken from the literature (see Discussion for more details).^{12,16,32}
 265 Random sampling between these minimum and maximum recovery factors was also
 266 incorporated into the Monte Carlo simulation. A summary of the ranges used are displayed
 267 in Table 1 below. This led to a final equation in R-Studio being run with 20,000 iterations:

$$\begin{aligned}
 & \text{Recoverable reserves} \\
 &= \text{sampled bulk rock volume} \times \text{sampled porosity} \\
 &\times \text{sampled oil saturation} \times \text{sampled NTG} \\
 &\times \text{sampled recovery factor} \times \text{formation volume factor}
 \end{aligned}$$

272 Table 1 – Summary table of ranges used within Monte Carlo Analysis

ROZ Parameter	Ranges used in Monte Carlo
Bulk Reservoir Volume m ³ (geo-cellular volume)	797,510,075 – 1,165,591,647
Water Saturation (well logs)	0.58 - 0.94
Porosity (core tests)	0.17 - 0.21
NTG (well logs)	0.44 - 0.74
Recovery factor	0.05 - 0.25

273

274 Results and Discussion

275 As can be seen in Figure 6, oil was present at low saturations at wells that are interpreted
 276 to penetrate the ROZ. Mean oil saturation across the 4 wells is 14% (stdev 9.8%), when
 277 calculated using core analysis data. Using well log resistivity data to estimate oil saturation
 278 leads to a higher mean oil saturation. The mid value water saturations for the sand intervals
 279 within the Forties Sandstone Member, based on the Archie water saturation method, were
 280 calculated to lie between 71% and 85%, with minimum values lying between 58% and 72%
 281 and maximum values lying between 80% and 94% (Table 2 in Supplementary Information).
 282 Using the same Archie water saturation method for all S_w data points in the four wells, a
 283 mean value of 74% - 26% oil saturation- (st dev 16%) was found. These higher and likely
 284 more representative oil saturations calculated using Archies water saturation method were
 285 used to calculate the oil in place for the South Pierce ROZ.

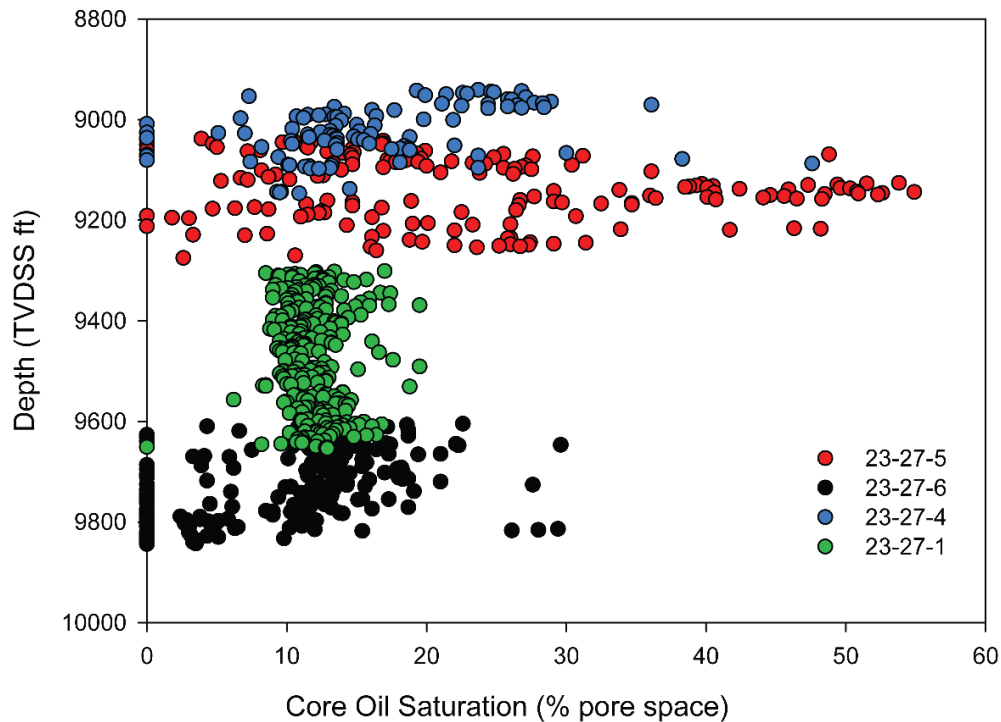


Figure 6- Compilation of core residual oil saturations from laboratory core tests at the four wells thought to cut through the ROZ at the South Pierce Field. The saturations given represent % pore space. Across the 4 wells the average core oil saturation is 15% but reaches values of up to 55%. Saturations calculated by well log analysis are higher at 26% average. Reservoir modelling and real field developments show that 5-25% of this oil can be recovered and can add additional commercial reserves not previously included in a fields reserves estimates (see Discussion for more details).

Using a Monte Carlo approach for the ROZ at South Pierce, oil in place values of 106, 179 and 291 MMbbl for P90, P50 and P10 respectively were estimated for the ROZ. Recoverable oil reserves for the South Pierce ROZ are estimated at 7, 17 and 34 MMbbl for P90, P50 and P10 respectively (Table 2). Given the main oil column in the Pierce Field had initial recoverable reserve values calculated of 42, 84 and 120 MMbbl for P90, P50 and P10 respectively,²⁸ it can be estimated that the CO₂EOR potential of the ROZ at the South Pierce Field adds around 20% to the recoverable reserves at the Pierce Field.

Table 2 – Summary of Monte Carlo results for CO₂ EOR from the ROZ at South Pierce. Recoverable reserves estimated using a range of recovery factors of 5-25% and a formation volume factor of 1.5. CO₂ demand is a minimum commercial requirement, calculated using storage factor of 0.33 tCO₂/bbl of oil produced. CO₂ storage is a maximum potential calculated using a storage factor of 0.9 tCO₂/bbl of oil produced.

	Min	Mid	Max
Forecast	P90	P50	P10
Oil in Place m3	16,822,843	28,473,651	46,259,511
Oil in Place (MMbbl)	106	179	291
Recoverable Reserves (MMbbl)	7	17	34
CO ₂ Demand (Mt)	2	6	11
CO ₂ Storage Potential (Mt)	6	15	31

CO₂ storage at Residual Oil Zones

It is thought that CO₂ EOR from ROZ will have similar operating parameters to CO₂ EOR operations that produce from conventional oil fields.¹² During the CO₂ EOR process residual trapping of CO₂, CO₂ dissolution and inefficient CO₂ sweep results in large fractions of injected CO₂ being stored permanently in the reservoir pore space and fluids.^{33,34} However a proportion of the CO₂ that is injected will return to the surface and be recycled. If recycled CO₂ is not diverted for injection in a different field it can be assumed that all CO₂ injected to increase recovery at a field will be stored at the end of the project (minus any CO₂ lost as fugitive emissions).³⁵

Based on CO₂ storage factors presented by Ferguson et al., Godec et al. and SCCS,^{36–38} a figure of 0.33 t/bbl was chosen to estimate the CO₂ demand at the ROZ at South Pierce. When applied to the value of recoverable reserves detailed in Table 2, the CO₂ demand at South Pierce ROZ is 2, 6 and 11 Mt of CO₂ for P90, P50 and P10 respectively. These estimates do not represent a maximum capacity for the zone, but only estimate the mass of CO₂ that is required to recover oil from the ROZ. If the storage factor of 0.9t CO₂/bbl, which represents CO₂ storage optimised CO₂ EOR where additional CO₂ is injected into the aquifer below^{35,39} is used, higher CO₂ storage estimates of 6, 15 and 31 Mt for P90, P50 and P10 respectively are found (Table 2). There are then a range of possibilities to store increasing amounts of CO₂ by utilising the active aquifer in addition to the reservoir. As first defined by the International Energy Agency,³⁹ storage of CO₂ in excess of the minimum, we title CO₂ EOR+ will require either a political and regulatory mandate, or a financial payment/fine avoidance to reward CO₂ stored.

335 **North Sea Residual Oil Zone potential**

336 We show in this study that the South Pierce Field holds potential for CO₂ EOR development
337 in the ROZ. Most geological plays for conventional hydrocarbon exploration are specified
338 around a combination of age of geological strata with structure or stratigraphic layering to
339 physically trap buoyant migration within a basin. By contrast, identification of ROZ plays
340 requires a different approach. Based on work by Dennis et al.,^{20,21} we have identified
341 multiple hydrodynamic ROZ targets, with tilted OWC in the Central Graben. These are
342 geographically grouped in the region affected by deep aquifer outflows draining the high
343 geopressure parts of the deep North Sea. In contrast to conventional hydrocarbons, this
344 play is controlled by brine flow in the deep subsurface, and so spans between a range of
345 reservoir ages and structure types. Hydrodynamically controlled tilted OWCs have been
346 proposed in fields ranging in age from Jurassic^{40,41} to Cretaceous^{20,40,42–44} and Palaeocene^{20,45}
347 in age. It is therefore likely that hydrodynamic ROZ potential exists in a number of other
348 North Sea Fields.

349 **CO₂EOR recovery factors at Residual Oil Zones**

350 This study highlighted the existence of hydrodynamically controlled ROZ in the North Sea by
351 interpreting well data⁴⁶, however the recoverability of oil from these zones is one of the key
352 areas of uncertainty. In this work, it was unfeasible to conduct core flood tests on core from
353 the South Pierce Oil Field to estimate irreducible oil saturation. Therefore we propose that
354 using analogue field wide recovery factors is sufficient to estimate the range of recovery
355 rates that occur when CO₂ flooding ROZ. While the 8 fields currently running CO₂ EOR from
356 the ROZ in the US are successful³², the duration of these projects is not long enough to have
357 confidently established a benchmark recovery factor. Hill et al. (2013)³² suggest a
358 conservative recovery factor of 20% of oil in place but state that recovery factors could
359 reach 30%, with a maximum achievable recovery factor based on CO₂ EOR recovery rates
360 on the main pay zone of 42%³². Trentham et al. (2012)¹² suggest that recovery rates of 10-
361 20% can be achieved from the ROZ. This is supported by the white paper by Kuuskraa
362 (2010), who suggests recovery rates of 17-18% of oil in place at the start of CO₂ injection.

364 For estimating recovery factors from North Sea ROZ, where development and well drilling
365 would take place offshore, with greater costs, it is likely that lower recovery factors will be
366 achieved. Although well spacing is expected to be higher in the North Sea a number of
367 studies have suggested that reservoir conditions will lead to similar surface volumes of CO₂
368 being needed for successful EOR operations. Goodyear et al. (2003)⁴⁷ state that although
369 the majority of UKCS fields lie at a greater depth than US fields, CO₂ densities (500-1000
370 kg/m³) would be similar due to the counteracting effect of higher temperatures. It is also
371 proposed that higher permeabilities and porosities in many UKCS oil fields will counteract
372 the well spacing issues. However Goodyear et al. (2011)⁴⁸ and Tzimas et al. (2005)⁴⁹
373 highlight the effect that these high permeabilities have on gravity segregation which will
374 also be amplified by large well spacing. They do however state that this detrimental effect
375 may be combatted by drilling horizontal wells, but that attention should be paid to the

376 inter-well pressure decrease that may drop reservoir pressure below the minimum
377 miscibility pressure when horizontal wells are utilised.

378 Given these uncertainties, the broad range of recovery factors used within this study (5-
379 25%) were chosen to represent the uncertainty in developing ROZ in an offshore setting in a
380 basin that has seen no CO₂ EOR development. It is recommended that a more detailed
381 reservoir model and reservoir simulation would be needed to increase the confidence of
382 the reserves potential.

383 It must also be noted that while this study focusses solely on the ROZ at the Pierce field and
384 does not assess the CO₂ EOR potential from the main oil column, in many cases it may be
385 best economically to develop ROZ alongside a broader CO₂ EOR development. As
386 referenced in the introduction of this paper, this is the most common practice in CO₂ EOR
387 projects that are producing from the ROZ in North America¹². There, wells have been
388 extended to penetrate through the main oil column and into the ROZ and produce oil from
389 both zones. In the North Sea this would also likely be a first step for a CO₂ EOR ROZ
390 development, where CO₂ can be used to increase recovery rates from a well characterised
391 main oil column, with ROZ adding to recoverable reserves and CO₂ storage resource as an
392 additional target.

393 **A low carbon oil production solution**

394 Although the reserves potential and CO₂ storage potential highlighted in this study are
395 significant, the development of ROZ with CO₂ EOR faces a number of non-scientific
396 challenges.⁴⁸ These include: profitability in a oil price lower than \$60/bbl, or field
397 decommissioning rather than engineering a change of use and extension of life.

398 The guaranteed availability of CO₂ is persistent paradox, given the IPCC's (2014)⁵⁰ strong
399 recommendations on Carbon Capture and Storage (CCS), and lack of any large scale
400 projects in Europe.⁵¹ During the formulation of a whole-system energy and climate policy, it
401 is important to recall that other EOR options, unlike CO₂ EOR, do not allow for a transition
402 towards CO₂ storage. Stewart and Haszeldine (2015),³⁵ showed that CO₂ EOR could produce
403 oil with a carbon intensity of 0.135 tCO₂/bbl of oil produced and as low as 0.06 tCO₂/bbl if
404 flaring and venting of produced methane gas was reduced to a minimum of 1%. Although
405 only marginally lower than production from some conventional oil fields (0.08 UK
406 conventional production),⁵² this carbon intensity is significantly lower than other sources
407 such as Nigerian and Venezuelan crude (Figure 7).⁵² For the South Pierce Field case study
408 this would mean that to produce 17 MMbbl of oil (P50 recoverable reserves), 2.3 Mt of CO₂
409 equivalent would be emitted or 0.88 Mt CO₂ equivalent if flaring is reduced to 1%. These
410 emissions are smaller than the 15Mt of CO₂ stored (P50) in the CO₂ EOR+ process. If
411 emissions from the transport, refining and final combustion of crude oil are also included
412 then an additional 7.9 Mt CO₂ equivalent (CO₂e) will enter the atmosphere. Therefore, as
413 seen in Figure 7, disregarding any emissions associated with the CO₂ before it is transported
414 offshore, this CO₂ EOR+ process could store more CO₂ than produced, with a net 6.6 Mt of
415 CO₂ stored. As seen in Figure 7, other oil production methods noted are net emitters of CO₂.

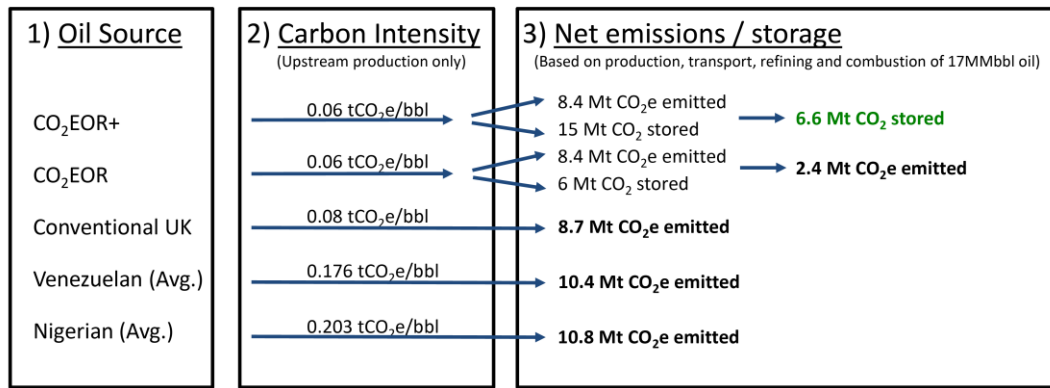


Figure 7 – Carbon intensity and net emissions / CO₂ storage from different oil sources. Carbon intensities represent upstream production only and are taken from Stewart and Haszeldine, (2015)³⁵ (CO₂EOR and CO₂EOR+) and from Gordon et al. (2015)⁵² (conventional UK, Venezuelan crude and Nigerian crude). Carbon intensities for CO₂ EOR and CO₂ EOR+ do not incorporate CO₂ stored. Net emissions / storage values in box 3 are shown in bold. Net emissions in box 3 represent emissions from producing (as in box 2), refining (0.03 tCO₂e/bbl), transporting (0.004 tCO₂e/bbl) and combusting (0.4 tCO₂e/bbl) 17 MMbbl of oil.³⁵ CO₂ EOR+ is the only process that stores more CO₂ than is emitted from the production, refining, transport and combustion of oil.

Conclusions

ROZ are not currently regarded as producible in the North Sea basin, so this oil is not declared as a resource. We identify a commercial opportunity to create new value by efficient use of existing hydrocarbon basins in an environmentally sustainable approach.

CO₂ flooding can be both used to maximise production in mature oil fields and store large volumes of CO₂. We recognise the first North Sea ROZ, as a potential resource, in the Pierce Oil Field, North Sea, Central Graben. Residual oil saturations at the South Pierce ROZ were on average 26%, of which a significant proportion could be produced by CO₂ EOR, and add up to 20% to the initial oil field reserves. While this study attempts to quantify the range of volumes of oil that could be produced and CO₂ that could be stored from ROZ, significant further research, such as detailed reservoir simulations, would be needed before any project is undertaken.

We propose that maximum utilisation of CO₂ (named CO₂ EOR+) will produce low carbon intensity oil and will store more carbon than is released from the production, transport, refining and combustion of the produced crude. With the development of CO₂ infrastructure, this practice can be a first step to CO₂ storage development in the North Sea basin.

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